Freshness and Reactivity Analysis in Globally Asynchronous Locally Time-Triggered Systems

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(kindly presented by Pierre-Loïc Garoche)

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Brief introduction and main contributions

Context: real-time embedded systems (e.g. avionic systems)

- built as functional chains from sensors to actuators through real-time tasks
- critical

$\Rightarrow$ need of formal verification methods

$\Rightarrow$ Main contributions:

- a verification method for end-to-end freshness and reactivity properties along functional chains
- via a Mixed Integer Linear Programming formalization
- scalable approach

Outline

1. Context: real-time embedded systems
   - An avionic case-study
   - Generalization: models and hypotheses
2. Related approaches
   - Previous work
   - Contribution v.s. previous work
3. The freshness analysis method
   - General idea
   - Modeling
   - Results on the case study
4. Extension to reactivity requirements
5. Conclusion and next work

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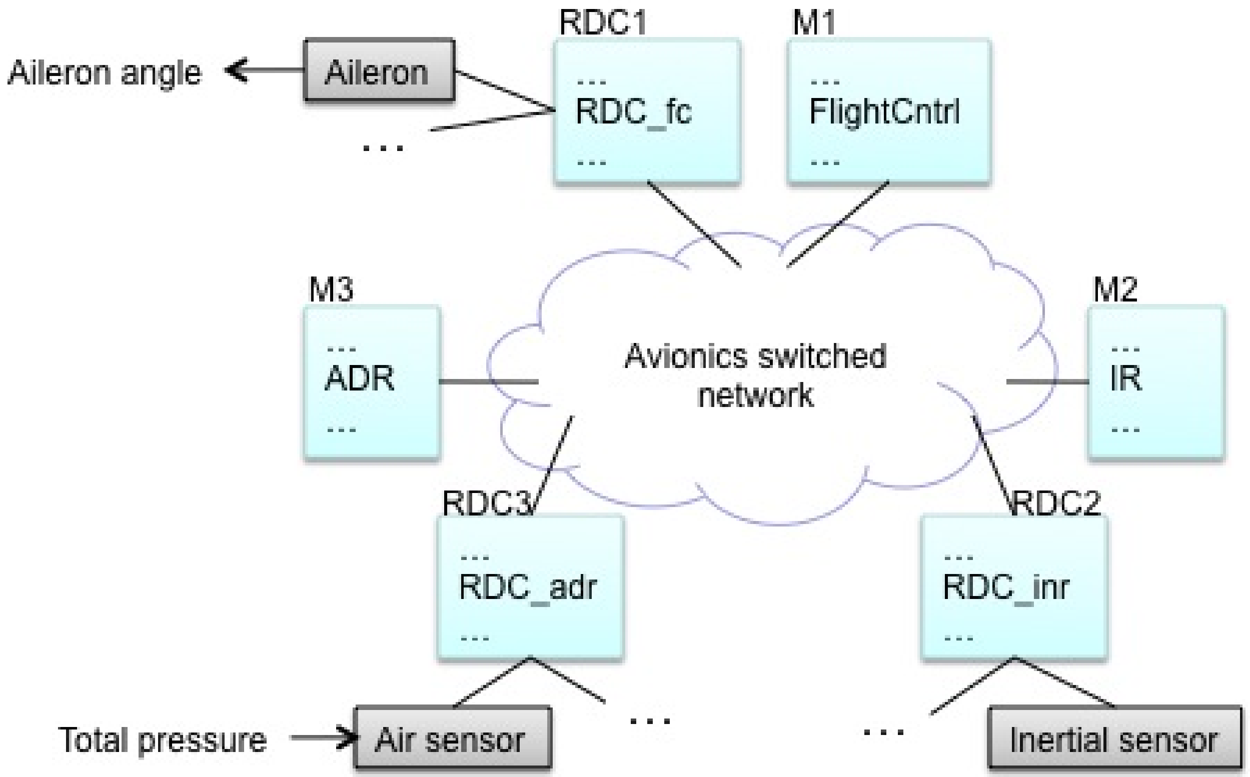
Outline

A Flight Control Chain (extract)



- computes the aileron angle w.r.t the current total pressure
- composed of 1 sensor, 1 actuator and 5 tasks mapped onto 5 processing modules
- tasks communicate through the avionics network

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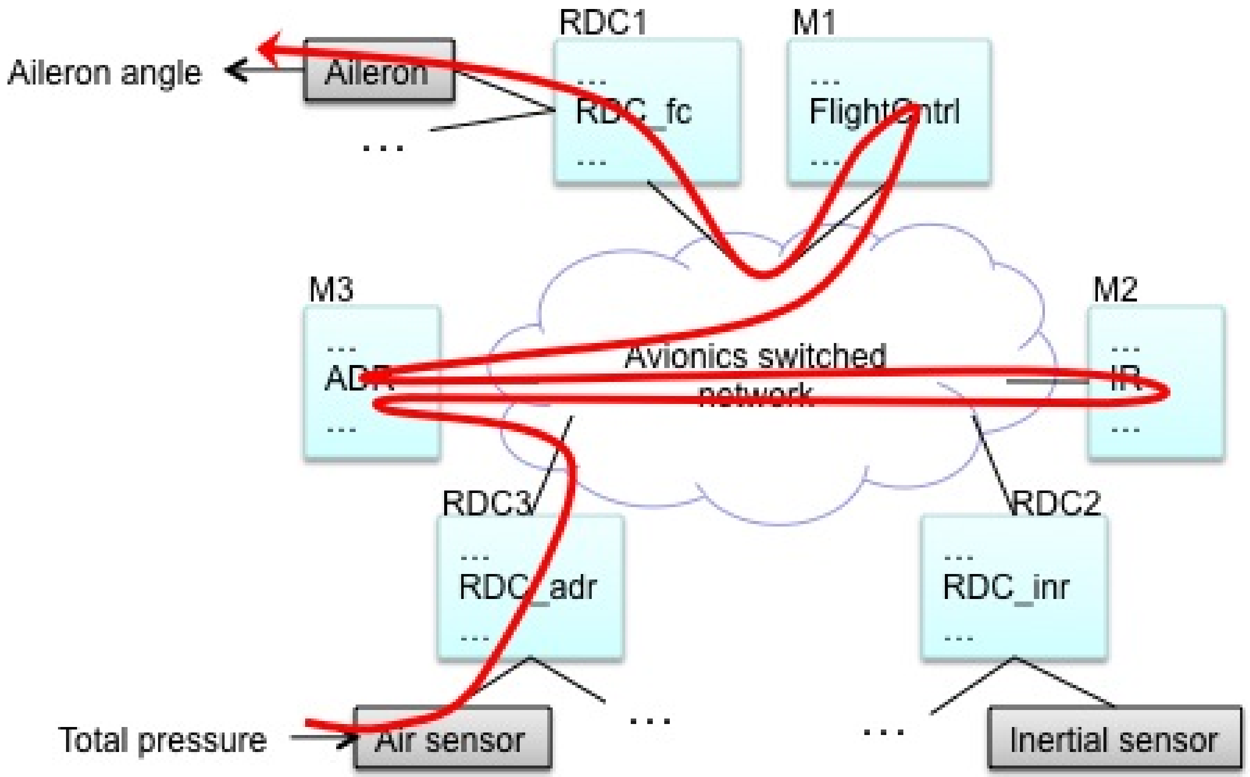

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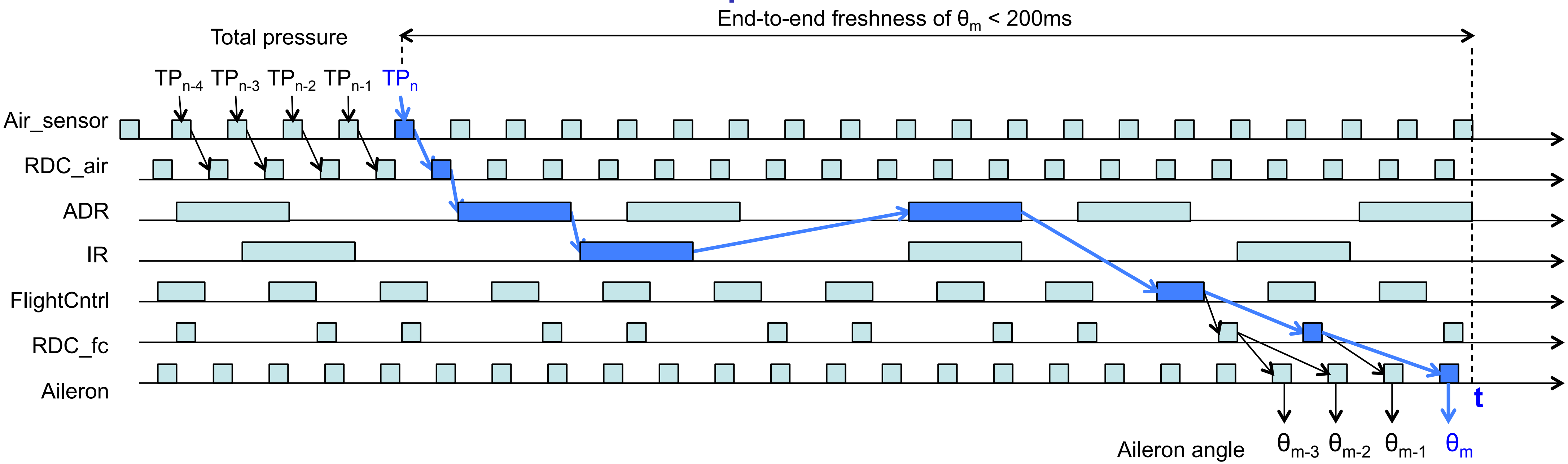
End-to-end freshness requirement



Requirement:

- for any date t, let θ_m the current aileron angle (at t),
- let TP_n the sample on which θ_m depends
- then freshness requirement: $t - date(TP_n) < 200ms$

Freshness

$F(t) = t - date(TP_n)$ is the freshness of the θ_m at date t: the age of the output with respect to its related input

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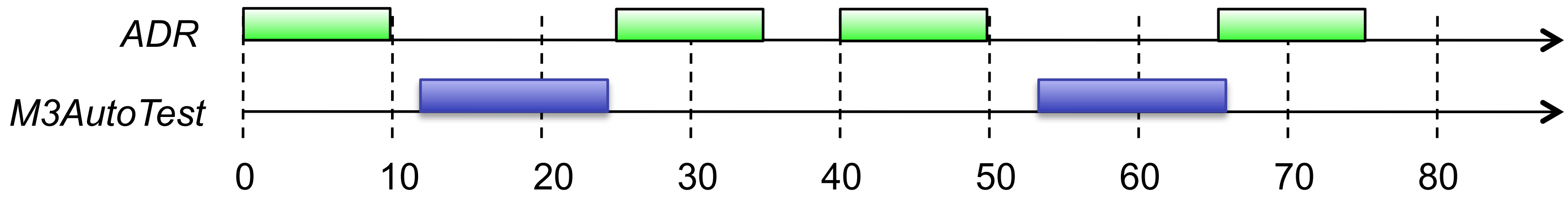
Model and hypotheses

System model:

- a set of periodic tasks $\Gamma = \{\tau_1, \ldots, \tau_N\}$
- statically mapped onto a set of modules $\mathcal{M} = \{M_1, \ldots, M_m\}$
- H_i is the hyper-period of the tasks mapped onto M_i.

Task model:

- each task τ_j on each module is characterized by a set of jobs $\{\tau_j(k)\}_{k=0 \ldots n_j}$ in the hyper-period of the module
- each job $\tau_j(k)$ is characterized by a timed interval $[b_j(k), e_j(k)]$ (static scheduling)



(example of module M_3)

Model and hypotheses

Communication model: tasks are assumed to communicate in an asynchronous way

- inputs are read at the beginning of the task
- outputs are produced at any time before the end of the task

Communication means:

- tasks running on the same module communicate through memory without delay
- tasks running on different modules communicate through a global network with bounded traversal times

Model and hypotheses

Global asynchronism: processing modules are globally asynchronous

- they can be shifted by an arbitrary amount of time.

$\Rightarrow$ Question: how to calculate the Worst Case Freshness (WCF) along a functional chain?

Outline

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Previous work

Local approaches

- The holistic approach (Tindell et al. (1994), Spuri (1996), . . .)
- Real-Time Calculus (Thiele et al. (2000))

$\Rightarrow$ Can be pessimistic since they consider worst case scenario locally on every component along the functional chain

$\Rightarrow$ Lead to impossible scenarios

Network analysis methods

- Network Calculus (Le Boudec et al. (2001))
- Trajectory Approach (Martin et al. (2006))

$\Rightarrow$ Only for network traversal time

Previous work

Global approaches

- Global modeling by timed automata and model checking (Carcenac et al. (2006), Ning Ge et al. (2012))

$\Rightarrow$ higher expressive power (more general temporal properties)

$\Rightarrow$ however, suffer from the combinatorial explosion

$\Rightarrow$ then, not efficient enough for realistic systems.

Outline

The contribution v.s. the similar approaches

- to focus on end-to-end freshness / reactivity properties
- to propose a global encoding as an Mixed Integer Linear Program

$\Rightarrow$ less pessimistic than local approaches

$\Rightarrow$ more scalable than model checking

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General idea

Principle

- to characterize all the possible behaviors of the functional chain with a set of constraints,
- to determine the worst case scenario among all these possible behaviors maximizing the freshness criteria
- can be done automatically by a solver.

$\Rightarrow$ Challenge:

- to identify the variables of the modeling, and then the constraints defining accurately the behavior of the system
- in a scalable way

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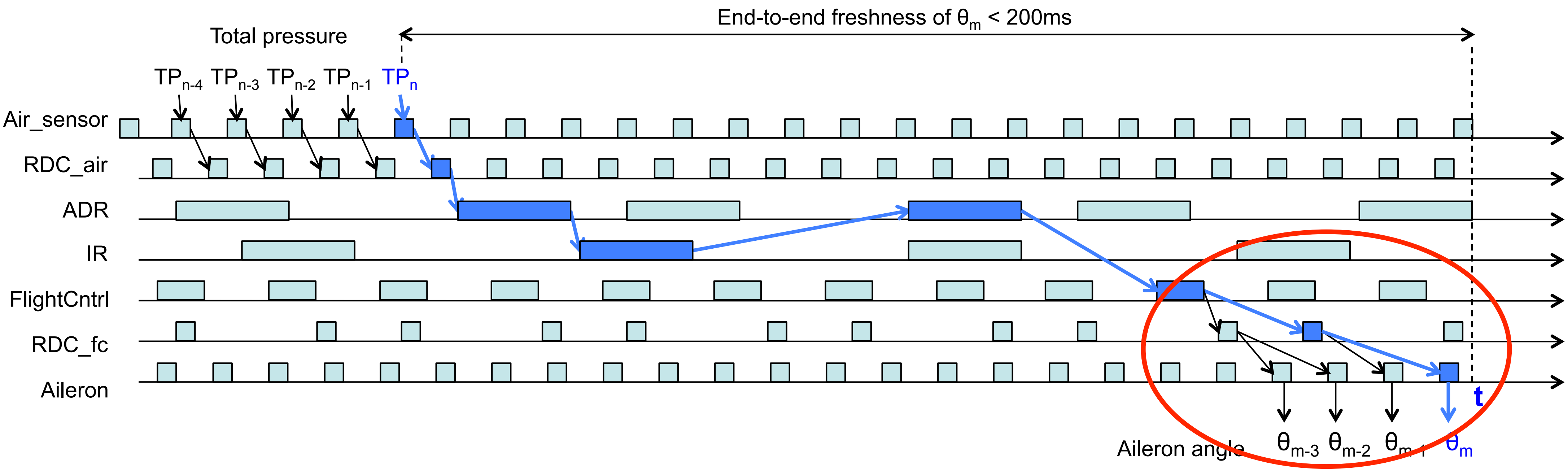
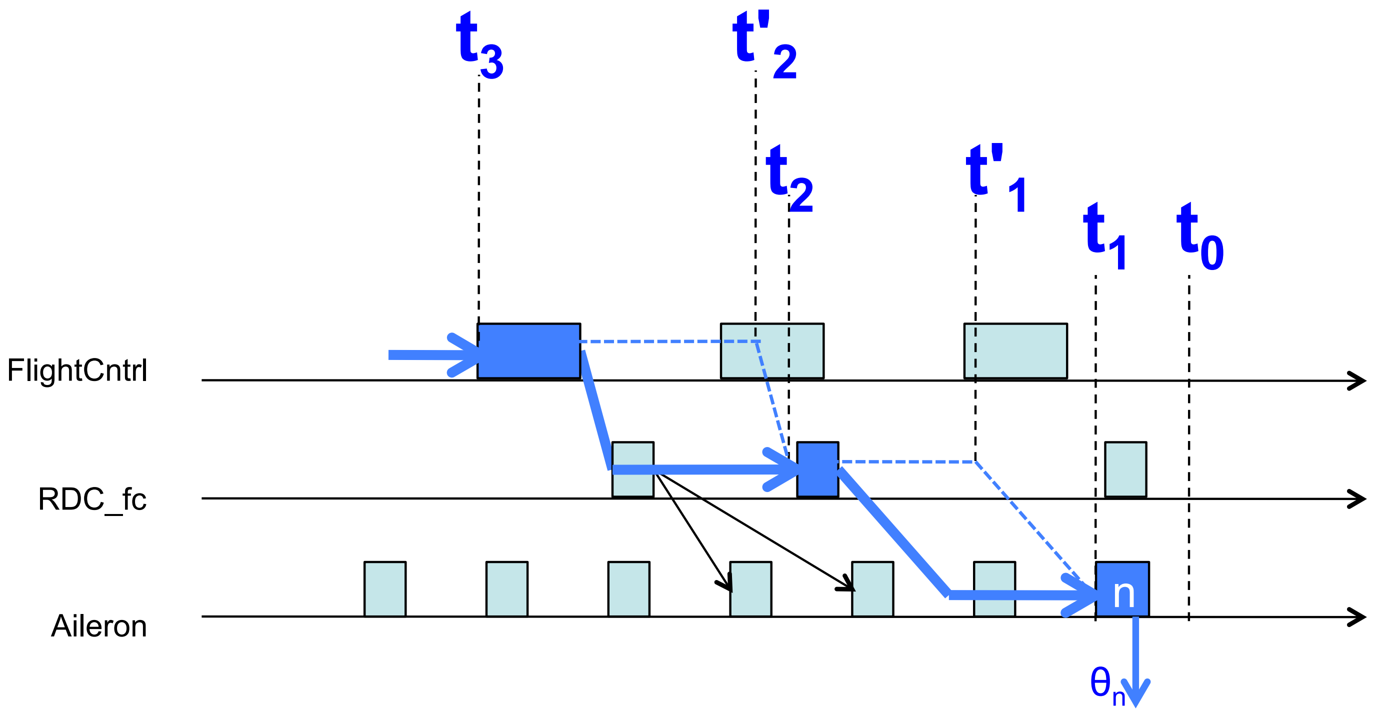
Case study recall



The modeling begins at the end
(freshness characterizes the output of the chain w.r.t. to the input)
$\Rightarrow$ Focus on the end of the chain

Case study recall

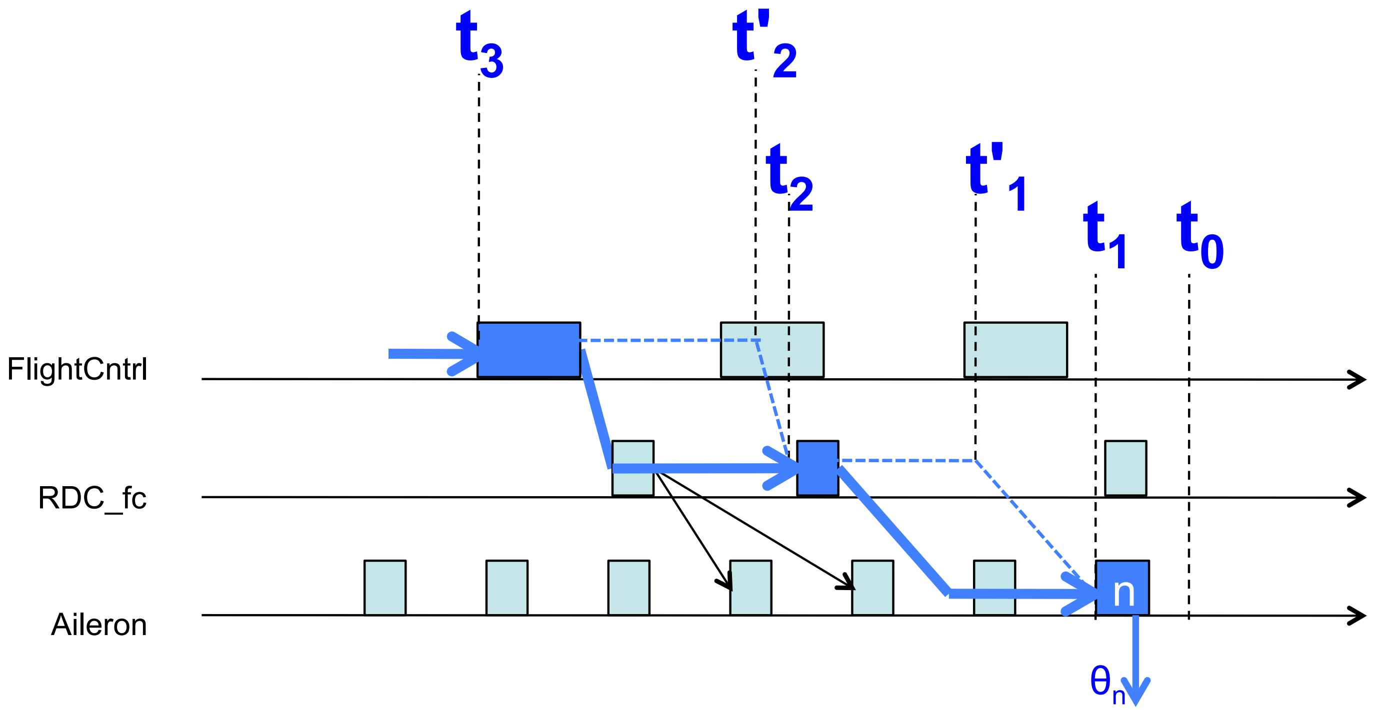


- t_0 = (arbitrary) date at which the output is observed
- n = occurrence of task "*Aileron*" which produces the output at t_0
- t_1 = date at which "*Aileron*[n]" begins and reads its input
- $t_1 - t'_1$ = communication time from "*RDC_fc*" to "*Aileron*"

$\Rightarrow$ t'_1 = date at which the output of "*RDC_fc*" is observed

- and so on...

Case study recall



$\Rightarrow$ Question: which constraints to characterize n, t_1, t_1', $t_2 \ldots$ from t_0?

Module (including sensors and actuators) modeling

- A module M_i is only characterized by an offset O_i
- Modules, sensors and actuators are asynchronous
- $\Rightarrow$ each O_i can be arbitrarily chosen

$\Rightarrow$ Constraints (case-study):

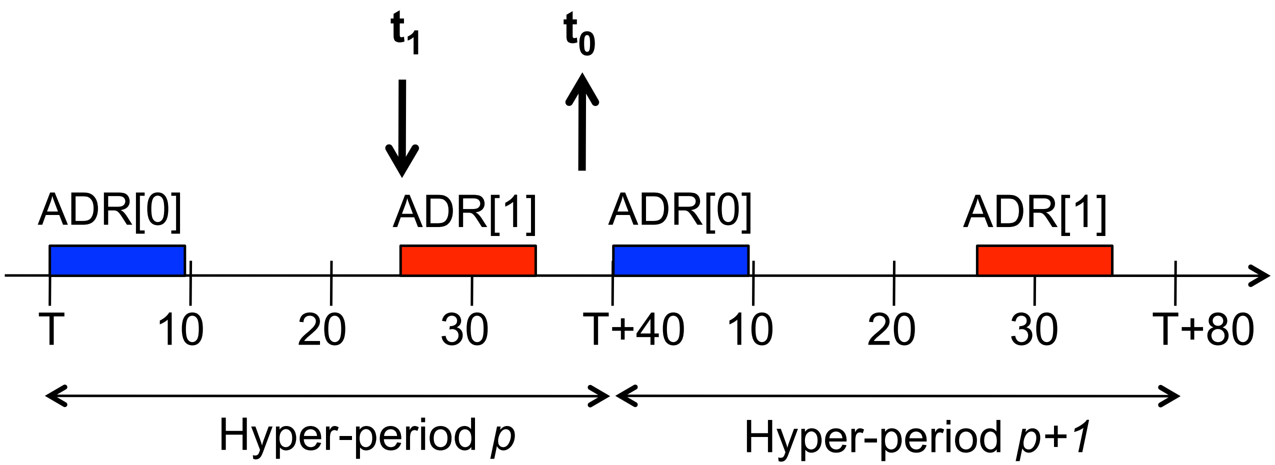
$$
\begin{array}{l}
O_{Aileron}, O_{RDC1}, O_{M1} \ldots \in \mathbb{R} \\
0 \leq O_{Aileron} \leq H \\
0 \leq O_{RDC1} \leq H \\
0 \leq O_{M1} \leq H \\
\ldots
\end{array}
$$

where H is the highest hyper-period of the system ($H = 40$ in the case-study)

Task modeling

- a task is characterized by a set of jobs in the hyper-period of its module

Example: *ADR* (2 jobs in $40ms$): $[0, 10]$, $[25, 35]$



Problem:

- t_0 the date at which the output is observed
- what constraints to determine which job produces the output and the date t_1 from t_0?

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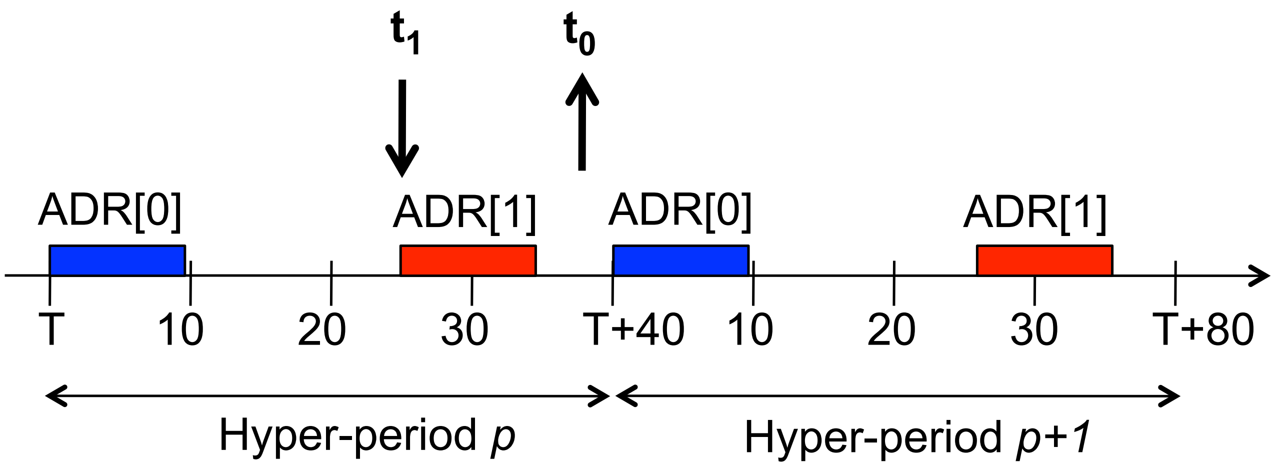

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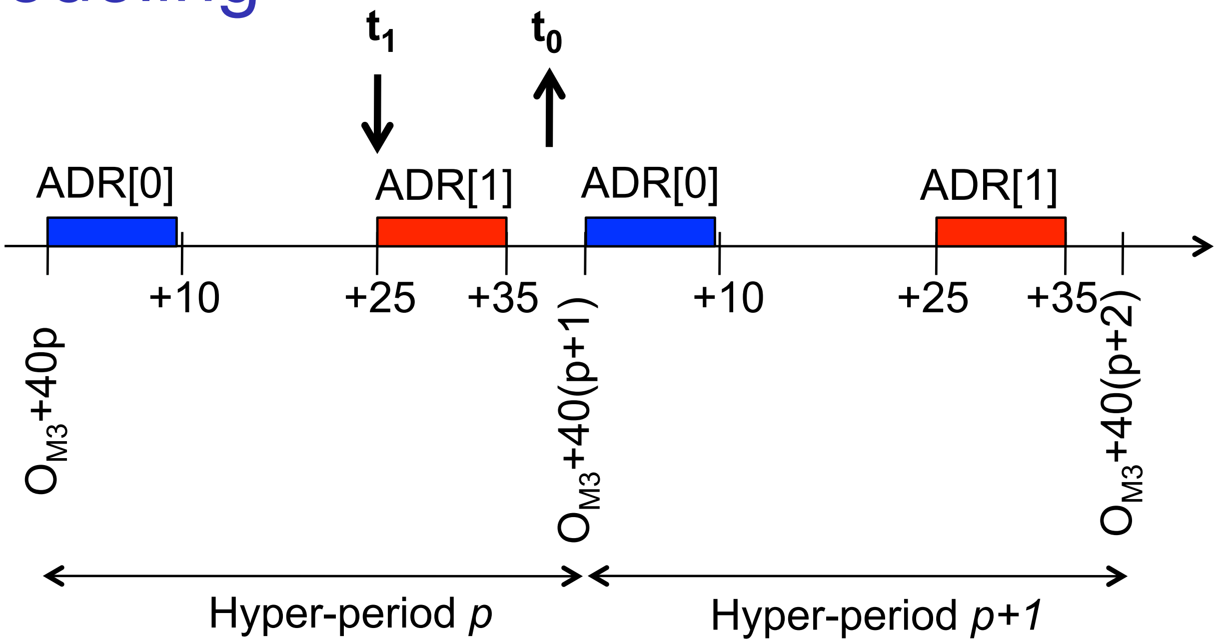


Let:

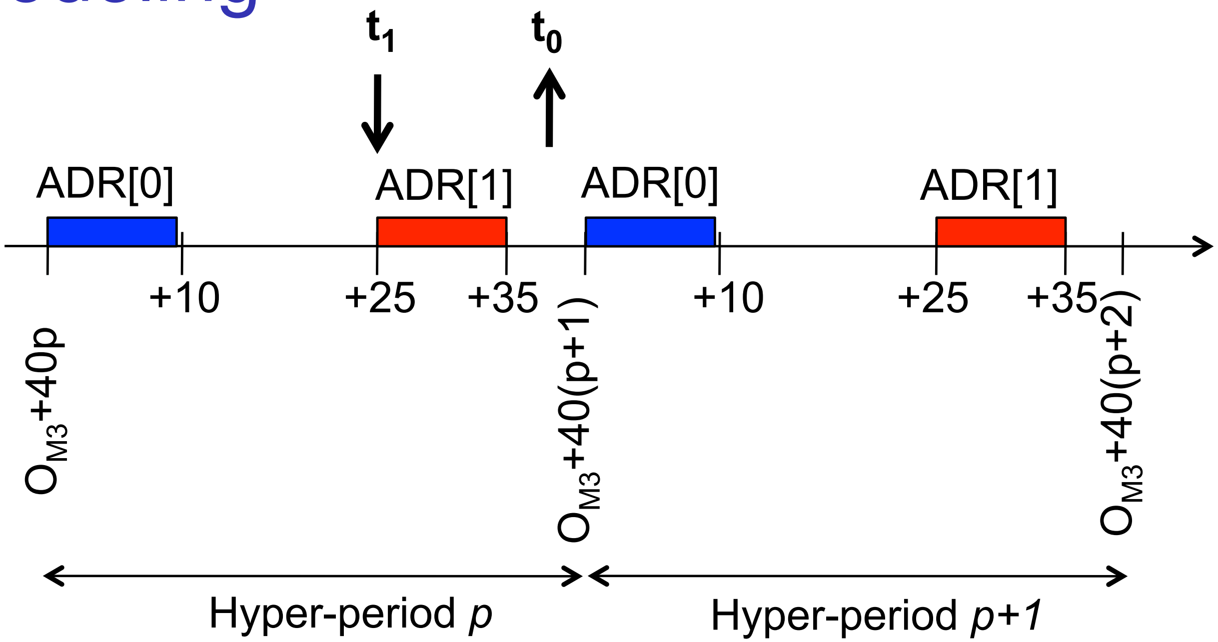
- $p \in \mathbb{N}$ (index of the current hyper-period at t_0)
- $B_{ADR[0]}, B_{ADR[1]} \in \{0, 1\}, B_{ADR[0]} + B_{ADR[1]} = 1$

Then:

$t_0 \geq O_{M3} + 40p + 0B_{ADR[0]} + 25B_{ADR[1]}$
$t_0 < O_{M3} + 40p + 35B_{ADR[0]} + (40 + 10)B_{ADR[1]}$
(recall: a job can produce its output at anytime in its time interval)

$t_1 = O_{M3} + 40p + 0B_{ADR[0]} + 25B_{ADR[1]}$

Task modeling



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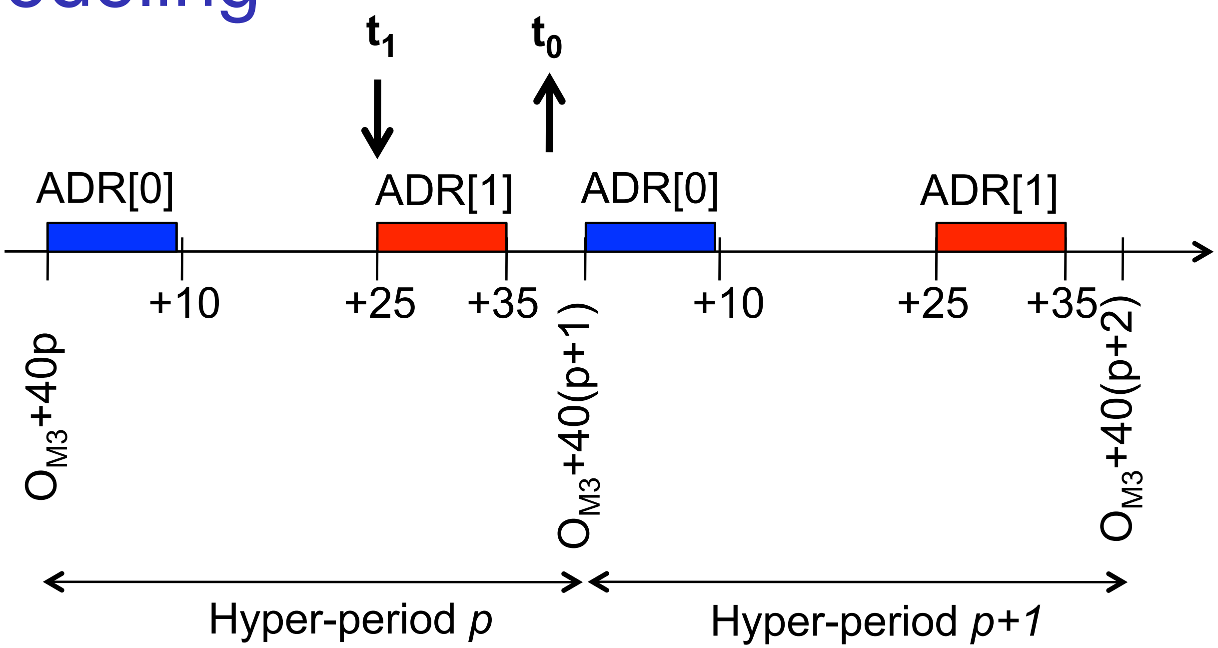

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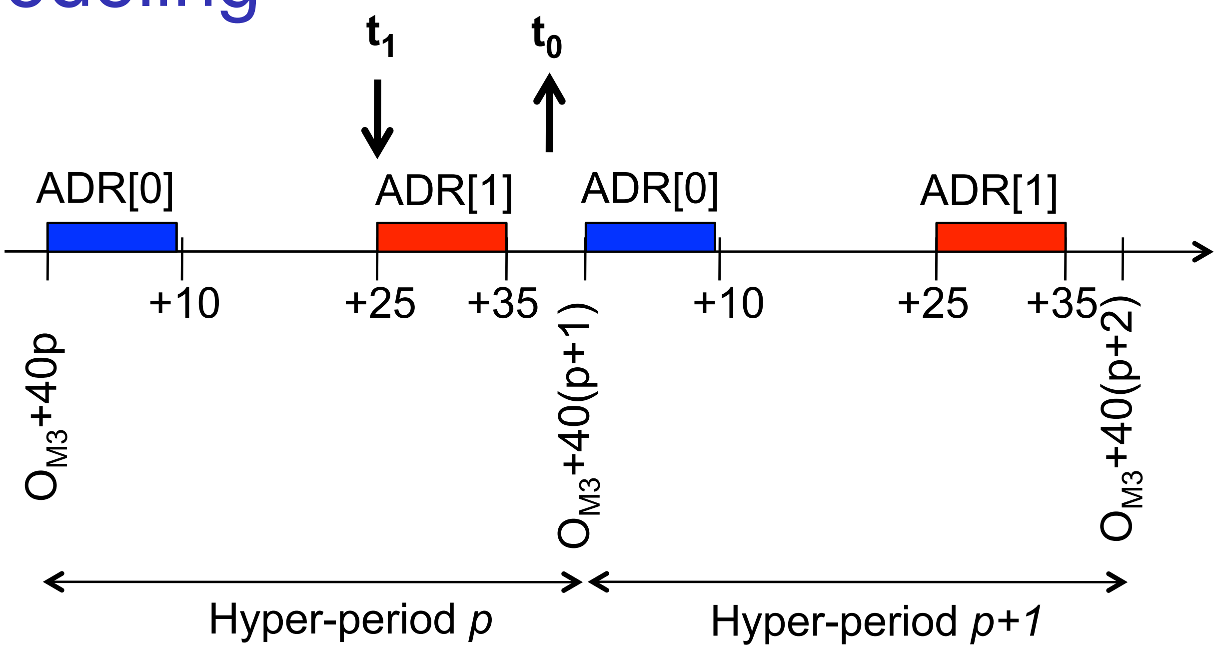

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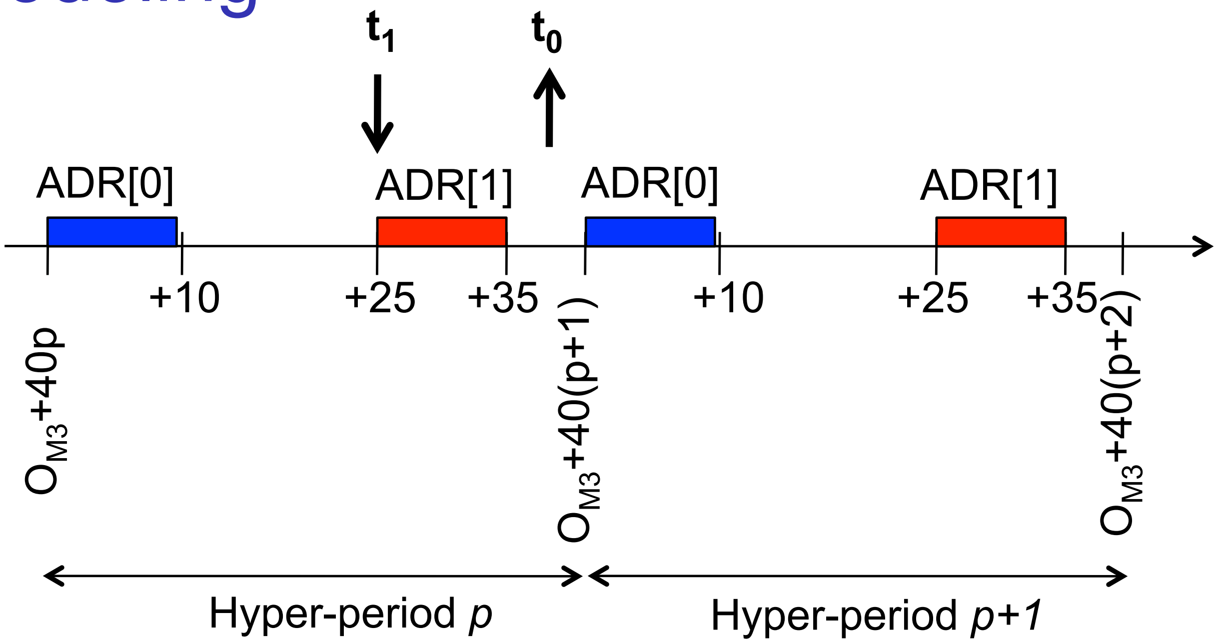

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Task modeling

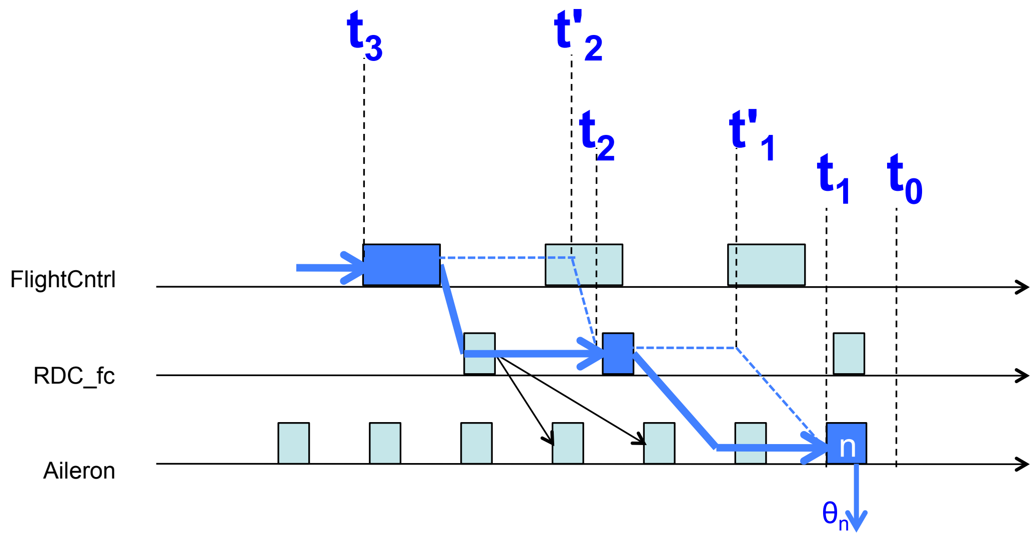
All solutions

$$(p, B_{ADR[0]}, B_{ADR[1]}, t_1) \in \mathbb{N} \times \{0, 1\} \times \{0, 1\} \times \mathbb{R}$$

satisfying the previous constraints characterize possible scenarios leading to the observation of the output at t_0.

Task modeling

Back to the case-study:

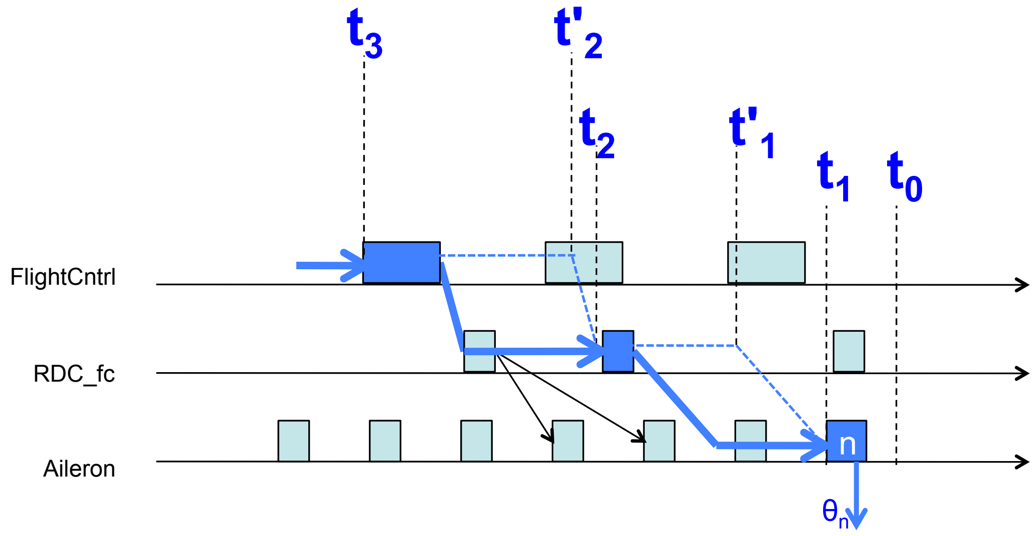


$t_0 \geq O_{Aileron} + 5p + 0B_{Aileron[0]}$
(recall: *Aileron* has only one job in its hyper-period (5ms))

$t_0 < O_{Aileron} + 5p + 6B_{Aileron[0]}$
(recall: the length of *Aileron* is 6ms)

$t_1 = O_{Aileron} + 5p + 0B_{Aileron[0]}$

Communication modeling



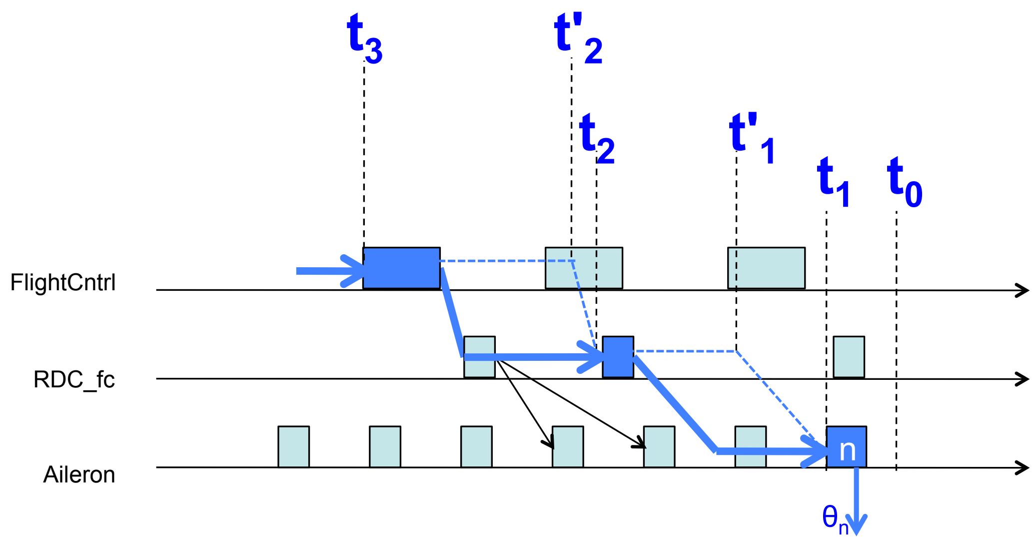
Let

- δ_{min} = the minimum communication time
- δ_{max} = the maximum communication time

$\Rightarrow$ Constraints:

$$t'_1 + \delta_{min} \leq t_1 \leq t'_1 + \delta_{max}$$

Communication modeling



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Latency requirement modeling

And so on ... up to

$$t_8 = O_{Air\_sensor} + 5p_8 + 0B_{Air\_sensor[0]}$$

(t_8 is the date at which the total pressure corresponding to the Aileron position at t_0 is read; p_8 is the number of the corresponding hyper-period of the Air sensor)

$\Rightarrow$ The freshness expression:

$$F = t_0 - t_8$$

$\Rightarrow$ The worst case freshness is obtained on a particular behavior maximizing F.

$\Rightarrow$ Opimization problem:

maximize: F

Latency requirement modeling

And so on ... up to

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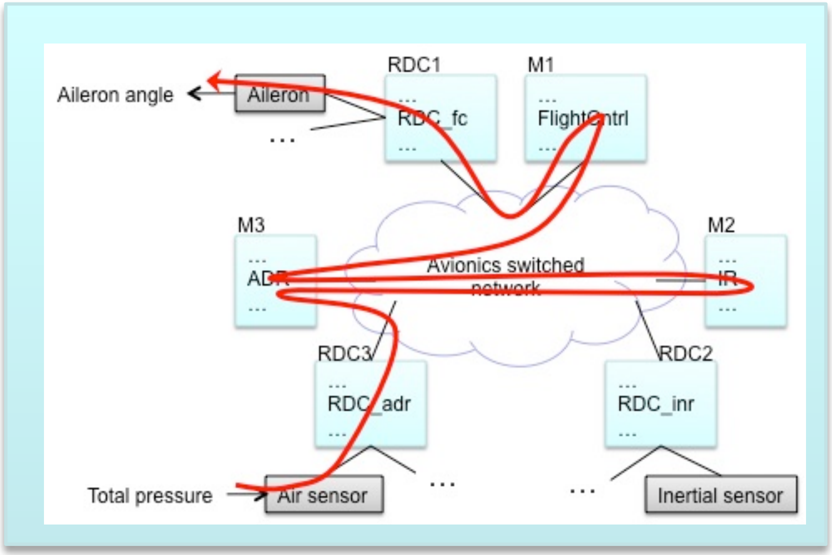
The tool chain



System model + WCF requirement

Encoding

//arrival in KC
$t_0 \leq O_1 + n_1 \cdot H_1 + 19Bkc_0 + 62Bkc_1 + 99Bkc_2$
$t_0 > O_1 + n_1 \cdot H_1 + 19Bkc_1 + 62Bkc_2 - Bkc_0 \cdot \mathit{Infty}$
$t_0 > O_1 + (n_1 - 1) \cdot H_1 + 99 - \mathit{Infty}(Bkc_0 - 1)$
$Bkc_0, Bkc_1, Bkc_2 \in \{0, 1\}$
$Bkc_0 + Bkc_1 + Bkc_2 = 1$

//output of KC
$t_1 = O_1 + n_1 \cdot H_1 + 31Bkc_0 + 74Bkc_1 + 11Bkc_2$

//timed channel from M_1 to M_2
$t_1 + 0.2 \leq t'_1 \leq t_1 + 2$

//arrival in $CockpitReqM$
$t'_1 \leq O_2 + n_2 \cdot H_2 + 31Bcr_0 + 76Bcr_1$
$t'_1 > O_2 + n_2 \cdot H_2 + 31Bcr_1 - Bcr_0 \cdot \mathit{Infty}$
$t'_1 > O_2 + (n_2 - 1) \cdot H_2 + 76 - \mathit{Infty}(Bcr_0 - 1)$
$Bcr_0, Bcr_1 \in \{0, 1\}$
$Bcr_0 + Bcr_1 = 1$

//output of $CockpitReqM$
$t_2 = O_2 + n_2 \cdot H_2 + 41Brc_0 + 101Brc_1$
...

MILP model

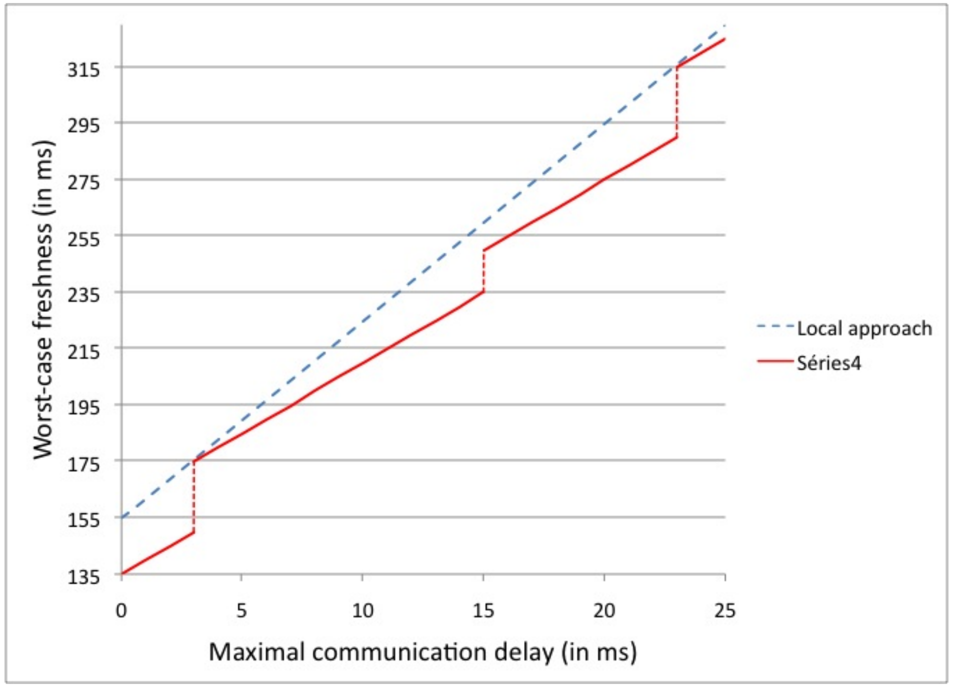
LP-solve

Worst-case latency +
a worst-case scenario

Outline

Results on the case study: global v.s. local approach

- global approach against the local one (i.e. sum of the local worst case)
- by varying the upper bound of the communication delays through the network



End-to-end freshness of aileron angle

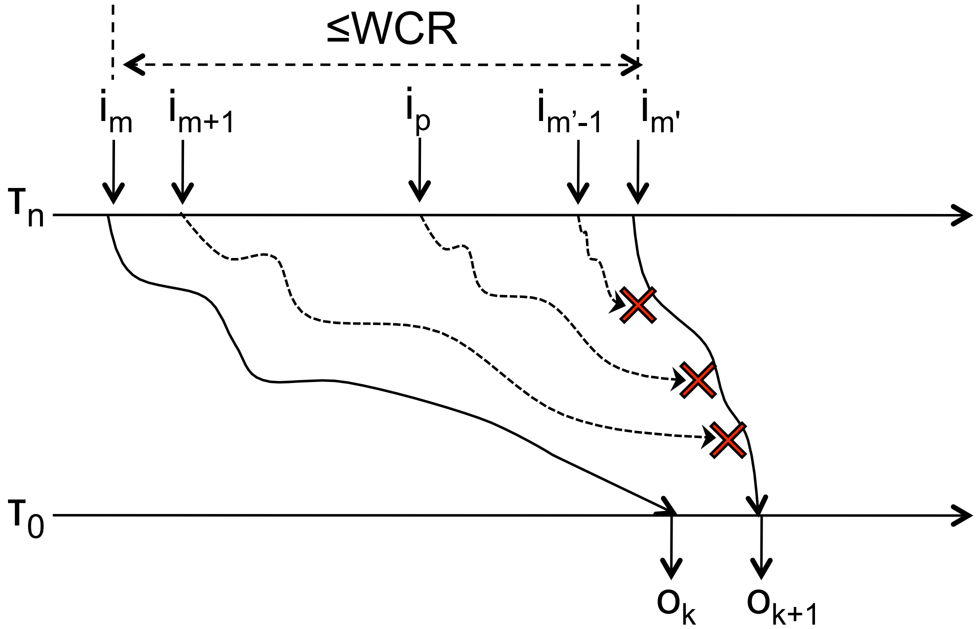
- red line = global approach
- dashed line = local approach

Outline

End-to-end reactivity requirement

End-to-end reactivity =

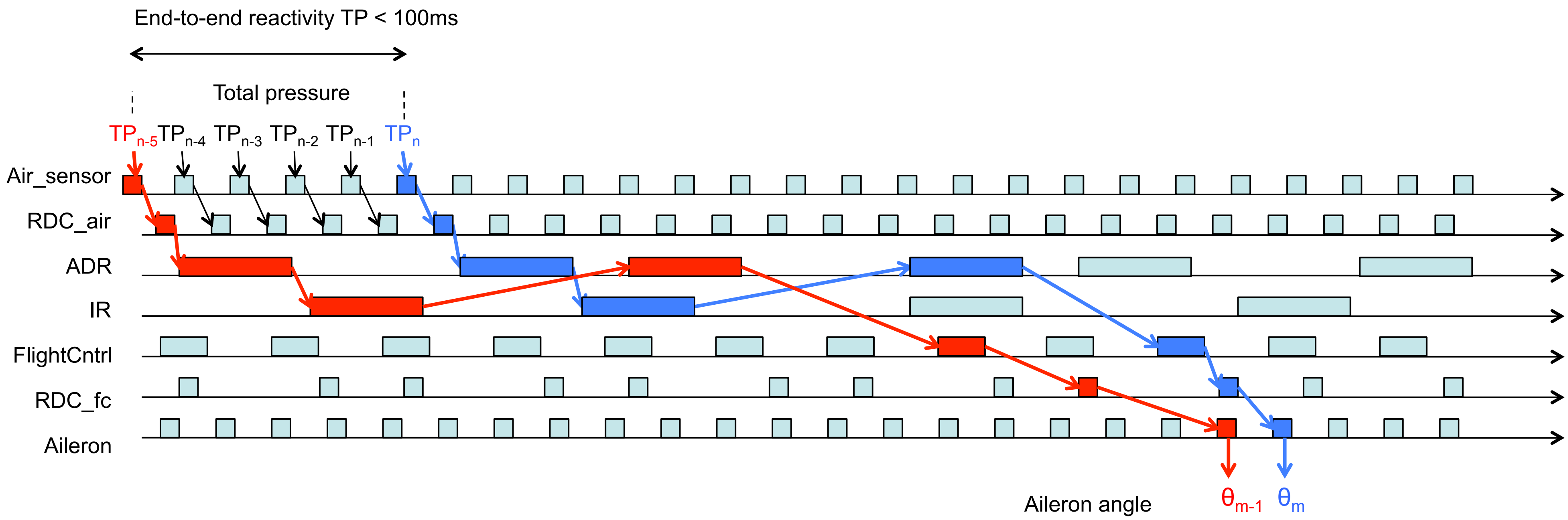
the minimal duration of an input signal, in order to be taken into account at the output of the chain



- i_m impacts o_k, $i_{m'}$ impacts o_{k+1}
- i_{m+1} to $i_{m'-1}$ do not impact the ouput (overwritten in the chain)

$\Rightarrow$ Worst Case Reactivity $\geq$ $date(i_{m'}) - date(i_m)$

End-to-end reactivity requirement



Approach:

- backtrack dependencies of two successive outputs
  - $\theta_m \rightsquigarrow TP_n$
  - $\theta_{m-1} \rightsquigarrow TP_{n'}$ (in the figure $n' = n - 5$)
- use the same contraints / variables as for freshness analysis
- maximize: $date(TP_n) - date(TP_{n'})$

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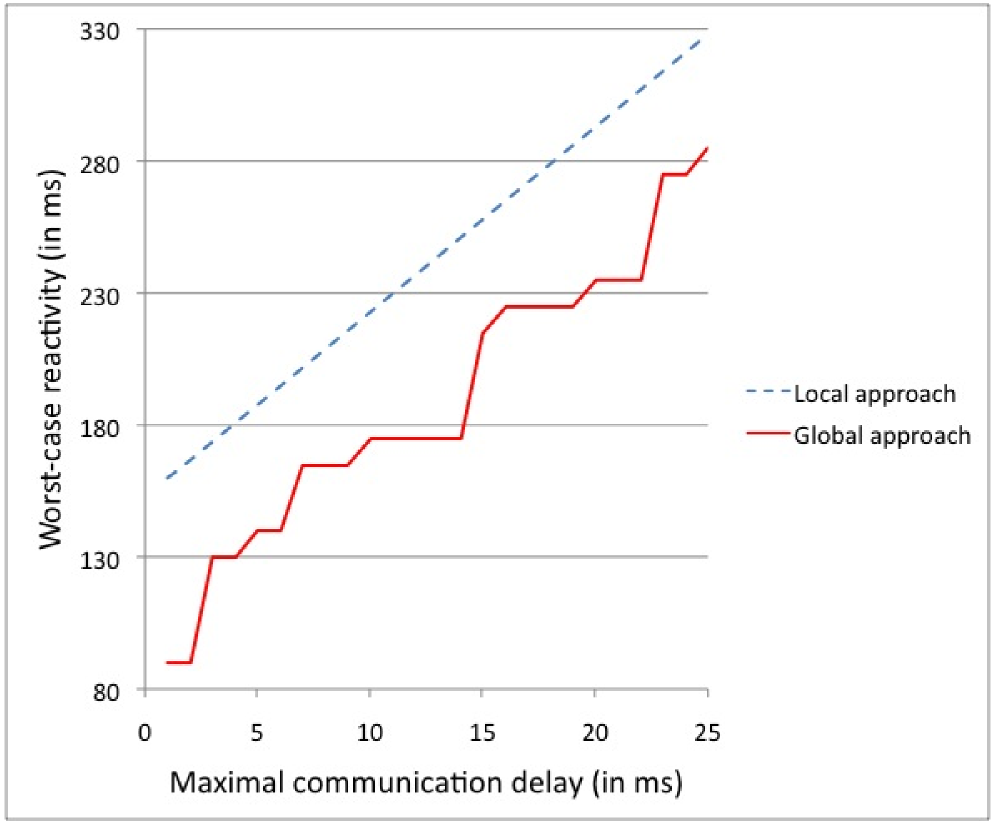

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End-to-end reactivity of total pressure

Outline

Conclusion and next work

Conclusion

- An efficient method for worst-case end-to-end freshness and reactivity analysis
- Extendable for best-case analysis
- Scalability:
  - takes less then 1 minute on the case-study
  - functional chain in realistic avionic systems contains at most 10 jumps from a task to another one (similar to the case-study)

  $\Rightarrow$ seems to be scalable

Next work

- Take into account the internal behavior of the tasks (i.e. latencies induced by the functional behavior of a task)

Thank you for your attention
(and many thanks to Pierre-Loïc Garoche)